Appendix 5

Reply to "Comment on the paper "On the determination of electron polytrope indices within coronal mass ejections in the solar wind""

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Submitted to the *Journal of Geophysical Research*, July, 2000.

PREPRINT/IN/92

LA-UR-00-3943

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Title: REPLY

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Submitted to: JOURNAL OF GEOPHYSICAL RESEARCH

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Reply

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We strongly disagree with the essence of the *Osherovich* [this issue] (hereafter Osherovich) comment on one of our papers [*Gosling*, 1999]. The following paragraphs provide the basis of our disagreement and elaborate on why we believe that none of the concluding statements in his Comment are true. Our most important point is that one can apply the model developed by Osherovich and colleagues to real data obtained at a single point in space to determine the polytropic index within magnetic clouds if and only if the highly idealized assumptions of that model conform to physical reality. There is good reason to believe that those assumptions do not provide an accurate physical description of real magnetic clouds in the spherically expanding solar wind.

The polytropic equation that relates pressure, P, and mass density, ρ, in a parcel of solar wind plasma as a function of time and distance has the form

$$P\rho^{-\gamma} = \text{constant}, \qquad (1)$$

where γ is the polytropic index. When one also assumes an ideal gas, this takes the form

$$T = Sn^{\gamma-1}, \qquad (2)$$

where T is the temperature, n is the number density, and S is the entropy. Rigorously, to determine γ it is necessary to sample temperature and density within the same plasma parcel at different radial distances from the Sun. In practice, the requirement of sampling the same plasma parcel can be relaxed if different plasma parcels sampled at different heliocentric distances start with essentially the same entropy and the entropy remains constant with distance as, for example, appears to be the case for protons in the high-speed wind at high heliographic latitudes near solar activity minimum [*Feldman et al.*, 1998].

Osherovich et al. [1993a] model magnetic clouds in the solar wind as cylindrical magnetic flux ropes with axially symmetric plasma and magnetic field properties that are invariant along extended cylindrical surfaces. In such a model the function $\Psi = rA_\phi$ is a constant on any cylindrical surface within the flux rope, where r is radial distance normal to the axis of the cylinder and A_ϕ is the azimuthal component of the vector magnetic potential (in cylindrical coordinates). As noted in his comment, Osherovich and colleagues also assume a polytropic relationship between gas pressure and mass density, an ideal gas equation of state, and uniform cylindrical expansion about the flux rope axis as a function of time. If such a model describes physical reality, then Osherovich is correct in stating that T and ρ on expanding cylindrical surfaces within the flux rope should be related to one another by

$$T = F(\Psi)\rho^{\gamma-1}, \qquad (3)$$

where $F(\Psi)$ is a constant for any given expanding cylindrical surface, but may vary from one surface to another. This equation simply states that all plasma parcels on an expanding cylindrical surface are equivalent in that they evolve in time in an identical fashion, as is required by the symmetry assumptions of the model. Since Osherovich and colleagues have assumed an ideal gas and a polytropic relationship between gas pressure and mass density, (2) must be satisfied as well, so that $F(\Psi)$ is directly related to entropy by

$$F(\Psi) = S(\Psi) / m^{\gamma-1}, \qquad (4)$$

where m is the average particle mass. They do not seem to have appreciated this simple connection between $F(\Psi)$ and entropy; their introduction of $F(\Psi)$ as something different from entropy has simply confused the issue. In reality, (3) reduces to (2) on expanding cylindrical surfaces and therefore does not depend explicitly upon a flux rope magnetic field topology; the essential assumptions are axial symmetry, invariant plasma properties along extended cylindrical surfaces, an ideal gas, a polytropic relationship between P and ρ, and uniform cylindrical expansion. If a flux rope of this nature were to pass over a spacecraft, each expanding cylindrical surface would be crossed twice, so that one would obtain pairs of temperature and density measurements of essentially equivalent plasma parcels on each expanding cylindrical surface within the flux rope. From these paired measurements one could make a series of two-point determinations of both $F(\Psi)$ and γ, as Osherovich claims.

Spacecraft measurements indicate that electron temperature, T_e, and density, n_e, are often negatively correlated as a magnetic cloud passes over a spacecraft. Osherovich and colleagues [e.g., *Osherovich et al.*, 1993*a,b*, 1995, 1998, 1999; *Fainberg et al.*, 1996; *Farrugia et al.*, 1995, 1999; *Osherovich and Burlaga,* 1997] have used such measurements together with their model assumptions to infer that the electron polytropic index, γ_e, is less than 1.0 within magnetic clouds and that $F(\Psi)$ typically is roughly constant in a given flux rope; in addition, they infer the presence of multiple flux ropes in some magnetic clouds. For different flux ropes they find different values of $F(\Psi)$ and different values of γ_e (but always < 1.0). If these determinations of γ_e are valid, then T_e must increase as the clouds expand and $S(\Psi)$ must be nearly constant throughout a given flux rope.

We wish to emphasize that the technique used by Osherovich and colleagues to determine γ_e within magnetic clouds is valid if and only if their model assumptions accurately describe the physical properties of real magnetic clouds. If magnetic clouds are not axially symmetric with uniform properties along extended cylindrical surfaces and do not expand in a purely cylindrical sense, then one does not obtain a series of 2-point samplings of essentially equivalent plasma parcels as a cloud passes over a spacecraft. The onus is on Osherovich and colleagues to prove that their model assumptions conform to physical reality and apply to real magnetic clouds in the spherically expanding solar wind. In this regard, the observed negative correlation between T_e and n_e within magnetic clouds is not proof that their assumptions are valid or a demonstration either that γ_e is less than 1.0 in magnetic clouds or that S is constant throughout a given cloud. Negative correlations between temperature and density at a single point in the heliosphere can and do arise for other reasons [e. g., *Gosling*, 1999]. We think it is highly unlikely that real flux ropes in the solar wind have axially symmetric and uniform properties along extended cylindrical surfaces, expand in a purely cylindrical sense, and have constant entropy throughout.

Osherovich notes that in their model the plasma density on a given expanding cylindrical surface must decrease with time as the flux rope expands. He also claims that the magnetic cloud observed by Ulysses on June 10, 1993 at 4.64 AU contained two separate flux ropes that passed Ulysses on June 10.00 - June 11.75 and June 11.75 - June 13.0, respectively. Figure 1 shows a plot of the proton density observed by Ulysses for these and the surrounding time intervals. Closest approach to the axis of the first flux rope or "tube" would have occurred approximately on June 10.88 and that of the second on June 12.38. It is immediately apparent that for many of the pairs of points equidistant in time on either side of closest approach to the tube axes, which would correspond roughly to the same expanding cylindrical surfaces in their model, the densities are not lower at the later times, in contrast to the model's assumption. The same is true if one uses the observed flow speed to convert time into a spatial distance. Clearly, these presumed separate flux rope tubes do not have uniform and axially symmetric plasma properties. Yet, the June 10, 1993 Ulysses event is often touted as a prime example supporting the model [e.g., *Fainberg et al.*, 1996; *Osherovich and Burlaga*, 1997; *Osherovich et al.*, 1999; *Osherovich*, this issue].

Making the further assumption that flux rope expansions are "self-similar", Osherovich and colleagues have found that expansion does not occur unless $\gamma_e < 1.0$ [e.g., *Osherovich et al.*, 1993*b*; *Osherovich*, this issue]. Since most clouds are observed to expand, he thus finds support for their model in their presumed experimental determinations of γ_e within magnetic clouds. But, as we have noted, those determinations of γ_e are themselves strongly dependent on the model assumptions. One cannot prove the validity of a model in this way. Further, flux rope expansion in the solar wind has been demonstrated in one-fluid MHD simulations where γ has explicitly been chosen to be 1.67 [*Vandas et al.*, 1996*a,b*], as well as in 3D analytical MHD calculations for values of γ ranging from 1.2 to 1.67 [*Chen and Garren*, 1993; *Chen*, 1996, 1997]. *Chen* [1996], who does not assume that flux ropes are axially symmetric cylinders, ascribes this difference in results to the difference between a 3D and a 2D calculation and Osherovich et al.'s neglect of the radial variation in pressure in the background solar wind in which real magnetic clouds are embedded.

Our own one-fluid simulations have been concerned primarily with dynamic effects associated with coronal mass ejection, CME, expansions, such as the forward-reverse shock pairs associated with expansions driven by high internal CME pressures [*Gosling et al.*, 1994*a,b*, 1998; *Gosling and Riley*, 1996; *Riley et al.*, 1997]. Usually in these and similar simulations [e.g., *Odstrcil and Pizzo*, 1999*a,b*] it is assumed that $\gamma = 1.67$. However, as we have previously noted [e.g., *Gosling*, 1999], other choices of $\gamma > 1.0$ have only a minor effect on the overall dynamics of these expansions, which is where our primary interest lies in these particular simulations. We have never claimed that a choice of $\gamma = 1.67$ provides a reasonable estimate of electron temperature evolution within CMEs. Indeed, we believe that smaller (but > 1.0) values probably better describe the electron thermal evolution within expanding CMEs in the solar wind. Thus the comparison shown in Figure 1a by Osherovich, which shows predictions for $\gamma = 1.67$ and which Osherovich claims is what we would predict, is not what we would advocate for electrons within CMEs in the solar wind, be they magnetic clouds or otherwise. Moreover, in attempting to make the comparison seem as poor as possible Osherovich conveniently ignores the fact that electron temperatures within CMEs in the solar wind at 1 AU often are considerably greater than 1×10^5 K [*Gosling et al.*, 1987]. We find no basis for his claim that "...no polytropic index can accommodate the evolution of temperature in magnetic clouds, if Formula (4) is used." We also stand by our previous comments [*Gosling*, 1999] to the effect that there is no observational evidence to support the idea that electron temperatures within expanding magnetic clouds, or expanding CMEs in general, increase with increasing heliocentric distance at any distance from the Sun. Indeed, the evidence is to the contrary. For example, we have recently obtained widely separated (in heliocentric distance) 2-point measurements of the same magnetic cloud and found that both T_e and n_e decreased with increasing heliocentric distance despite the fact that at each spacecraft T_e and n_e were negatively correlated [*Skoug et al.*, 2000*b*].

In order to circumvent some of the difficulties associated with predictions of ever increasing values of electron temperature as a magnetic cloud expands, Osherovich now incorporates an electron heat flux term into the polytropic equation, where he seems to advocate that the only heat flux that affects electron temperature within a flux rope is through the walls of the flux rope tube, transverse to the magnetic field. We fail to understand how electrons can carry a significant flow of heat transverse to the magnetic field in the essentially collisionless solar wind or how this new version of their model makes any more physical sense than the previous one.

Osherovich claims that the choice of $\gamma > 1.0$ in our simulations leads to a positive correlation between T and ρ at a fixed point in space, which he notes is contrary to electron observations within magnetic clouds. However, in many of our simulations we obtain neither a linear nor a positive correlation between log T and log ρ (or n) at a fixed point in space [*Riley et al.*, 2000]. The relationship between T and n at a fixed point depends on the nature of the initial perturbation at the inner boundary of the simulation and on heliocentric distance. We obtain a straight line with positive slope in log T vs. log n space at a fixed point in space only when the plasma introduced at the inner boundary is isentropic and remains unshocked as it propagates outward from the Sun. When both of these conditions are satisfied the slope of the log T vs. log n relationship at a single point does provide a direct measure of the value of γ used in the simulation.

In some of our simulations we obtain strong negative correlations between T and n at a single point in space [*Riley et al.*, 2000]. The upper panel of Figure 2 displays a random set of points in log T vs. log n space used to initialize a disturbance lasting 10 hours at 0.13 AU in a spherically symmetric, 1-dimensional, 1-fluid simulation in which $\gamma = 1.5$. The speed at 0.13 AU was held constant at 702 km s^{-1} and the random density/temperature disturbance was preceded and followed by extended intervals of constant density and temperature, and thus also constant entropy. The cross marks the value of density and temperature for this ambient surrounding wind. The simulation follows the evolution of the disturbance out into the heliosphere; the lower panel of Figure 2 shows the resulting log T vs. log n plot at 3.0 AU where the disturbance has evolved into a structure that is nearly in pressure balance. The cross in this panel denotes undisturbed ambient solar wind at 3 AU. All values of density and temperature are lower at 3.0 AU than at 0.13 AU owing to the spherical expansion of the solar wind and our choice of $\gamma > 1.0$. Points in the perturbed ambient wind (small dots) lie roughly along a straight line with positive slope (0.5), indicating that the perturbation to the surrounding, initially isentropic, ambient wind produced by the initial disturbance was devoid of strong shocks. On the other hand, points within the original disturbance pulse (large dots) lie roughly along a line of negative slope (-0.908) even though γ for the entire simulation was 1.5. The negative slope is a consequence of non-isentropic structure in the initial disturbance and evolution toward pressure balance. Thus, negative correlations between density and temperature at a single point in space within a CME or magnetic cloud may simply reflect the presence of (non-isentropic) structure in the initial disturbance close to the Sun and the tendency for such structure to achieve pressure balance as it evolves outward [*Gosling*, 1999; *Riley et al.*, 2000; *Skoug et al.*, 2000*a*]. And, of course, one can not directly infer the value of γ from the log T vs. log n plot within the simulated CME in this case.

Finally, Osherovich and colleagues give the impression that negative correlations between T_e and n_e are not observed in the solar wind except within magnetic clouds. However, recent work [*Skoug et al.*, 2000*a*] demonstrates that negative correlations between T_e and n_e are common in much of the solar wind, including within CMEs in the solar wind that are not magnetic clouds. This is consistent with previous studies of solar wind thermal core electrons [*Phillips and Gosling*, 1990; *Hammond et al.*, 1996]. That is, the negative T_e-n_e correlation in the solar wind does not depend on the presence of a magnetic structure with a flux rope topology. It has also been demonstrated that at 1 AU halo electrons do not contribute more to the total pressure in magnetic clouds than they do in other types of solar wind of comparable density [*Skoug et al.*, 2000*a*], contrary to statements by Osherovich.

To summarize, Osherovich's claim that essentially two-point, rather than single-point, measurements of T_e and n_e are made as a magnetic cloud passes over a spacecraft is valid if and only if the the highly idealized symmetry and uniformity assumptions of their model correspond to reality. If those assumptions are not physically correct then such measurements reveal nothing about the value of γ_e within magnetic clouds. It is up to Osherovich and his colleagues to show that their assumptions conform to physical reality for real magnetic clouds in the spherically expanding solar wind, but we have provided solid evidence that they do not. We have also emphasized: (1) Their $F(\Psi)$ is simply related to entropy. (2) A value of γ_e less than 1.0 is not required for flux rope expansion in the solar wind. (3) T and ρ are often not positively correlated in simulations where $\gamma > 1.0$. (4) Strong negative correlations between T_e and n_e at a single point in space can arise from non-isentropic structure within magnetic clouds and the solar wind in general even when $\gamma_e > 1.0$. (5) Negative correlations between T_e and n_e are observed in much of the non-magnetic cloud solar wind, making it unlikely that those correlations are related to the special magnetic topology of magnetic clouds or are a consequence of $\gamma_e < 1.0$. (6) Available evidence indicates that electron temperatures within magnetic clouds, and within CMEs in general, decline as those disturbances expand out into the heliosphere. (7) If a polytrope equation adequately describes electron evolution, the polytropic index is greater than 1.0 in magnetic clouds, in non-cloud CMEs, and in the solar wind in general.

Acknowledgments. The authors have profited from discussions on this topic with J. Chen and M. Thomsen. Work at Los Alamos was performed under the auspices of the U. S. Department of Energy with support from NASA and the Ulysses project. Work at SAIC was supported by NASA grant NASW-98007 and contract NAS4-96081.

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Figure Captions

Figure 1. Solar wind density measured by Ulysses at 4.64 AU and S32.5° during passage of a disturbance driven by an overexpanding CME that was also a magnetic cloud. The two separate, but adjacent, flux ropes within the CME/cloud identified by Osherovich and colleagues are indicated by the solid vertical lines. Dashed vertical lines indicate closest approach to the presumed axes of those flux ropes.

Figure 2. (**a**) Density-temperature points used to initialize a 10-hour disturbance in the solar wind at 0.13 AU in a one-dimensional (radial), one-fluid simulation. The cross marks the value of density and temperature in the surrounding ambient solar wind at 0.13 AU. (**b**) The resulting paired values of density and temperature at 3.0 AU. The solid curve is the best-fit straight line to plasma parcels that originated within the 10-hour disturbance at 0.13 AU. See text for full explanation. Adapted from *Riley et al.* [2000].

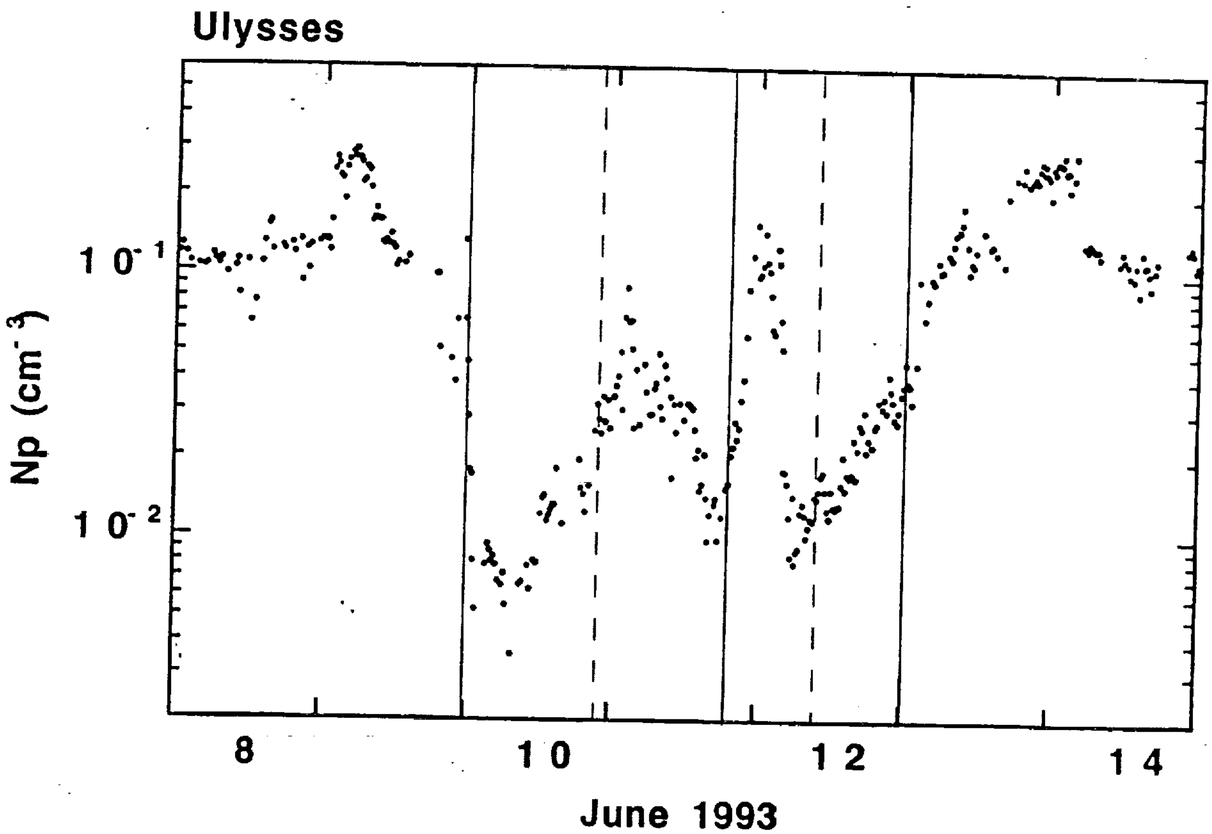

Figure 1.

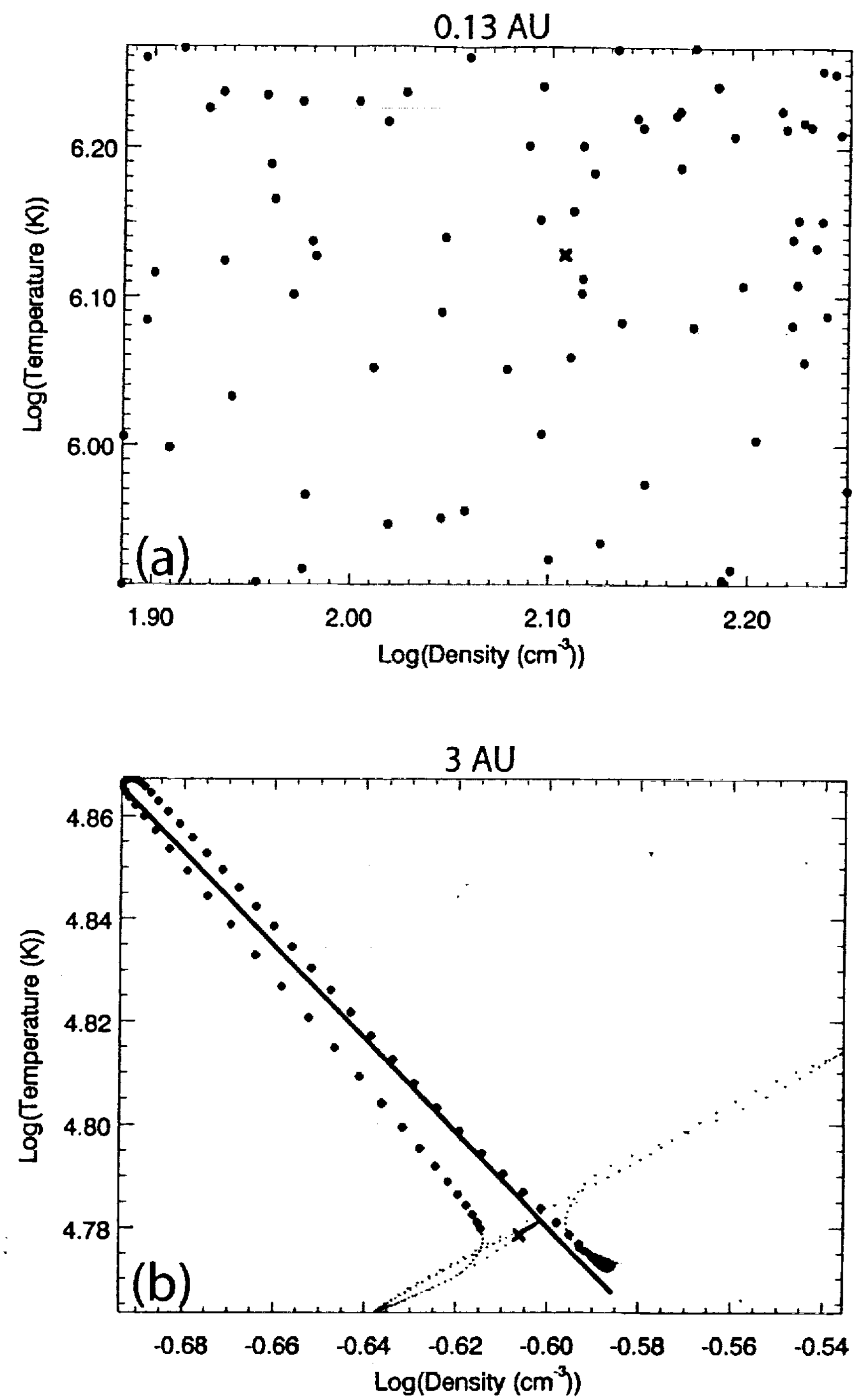
0.13 AU
Log(Temperature (K))
6.20
6.10
6.00
(a)
1.90
2.00
2.10
2.20
Log(Density (cm^{-3}))
3 AU
Log(Temperature (K))
4.86
4.84
4.82
4.80
4.78
(b)
-0.68
-0.66
-0.64
-0.62
-0.60
-0.58
-0.56
-0.54
Log(Density (cm^{-3}))

Figure 2.